Barriers to Protect Hilo from Lava Flows[1]

GORDON A. MACDONALD[2]

THE CITY OF HILO, on the island of Hawaii, lies on the flank of one of the world's most active volcanoes, Mauna Loa. For more than a century the danger of destruction of the city by lava flows has been recognized. Old documents recount the apprehension with which Hilo residents watched the advance of the lava flows of 1852 and 1855. In 1881 concern was even greater, as the flow front crawled within a mile of the shore of Hilo Bay. Early in his studies of Hawaiian volcanoes, the late Dr. Thomas A. Jaggar recognized the threat to Hilo, and for many years the safety of the city and methods by which it might be insured were among his principal concerns (Jaggar, 1931, 1949).

In 1937, following preliminary studies by the staff of the Hawaiian Volcano Observatory, Jaggar proposed the building of a barrier, or barriers, on the lower slopes of Mauna Loa to deflect lava flows from Hilo harbor and its immediate vicinity. Such a barrier would consist essentially of a great wall stretching diagonally across the slope. The purpose of the barrier would not be to hold back the flow, like a dam, but to turn the flow and direct it away from the vital area. In 1938 a study of the project was begun by the U. S. Engineer Department (now U. S. Army, Corps of Engineers). A route and design for the barrier were chosen, and the entire proposal was subjected to careful study. It was found in the estimate of the Engineer Department to be entirely feasible. The official report, in January 1940, stated: "The District Engineer believes it is possible to protect the harbor and city by a properly located and constructed barrier." The construction of the barrier was not carried out because it was considered not to be a justified function of the War Department (Jaggar, 1945: 340–341).

It is the purpose of this paper to review the need of protection for Hilo, and the methods by which it might be accomplished. When I first heard of the proposal to protect Hilo from lava by means of walls to deflect the flows, I was very doubtful whether the method could be successful. However, the study of active flows during 7 eruptions and of many older flows, in the course of 17 years of experience with Hawaiian volcanoes, has convinced me that such walls have an excellent probability of succeeding. Attempts to build diversion barriers during the 1955 eruption of Kilauea have not weakened that conviction, though they have shown that the walls must be carefully planned, and properly placed and constructed.

Whether barriers are likely to be needed, and whether successful barriers can be built, are questions properly falling within the field of the volcanologist. Answers to only those questions are attempted herein. The question of whether a barrier should be built involves complex considerations of relative values of the area to be protected, income to be expected from the area, effects of loss of the area upon the economy of surrounding areas, effects of displacement of population as a result of loss of the area and influence on adjacent areas, cost of construction of the barrier plus interest on the cost, the ability of the community (either locally or at large) to pay this cost, and no doubt other factors. There are also the legal questions arising from diversion of lava onto land that otherwise might not have been covered during that eruption. These questions fall outside the province of the volcanologist and must be decided by economists, sociologists, and lawyers.

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[1] Publication authorized by the Director, U. S. Geological Survey. Manuscript received Feb. 8, 1957.

[2] Present address, Department of Geology and Geophysics, University of Hawaii. Contribution No. 6, Hawaii Institute of Geophysics.

ACKNOWLEDGMENTS

Since the 1955 eruption of Kilauea the matter of lava barriers for the protection of Hilo has been the subject of frequent discussion with Jerry P. Eaton, geophysicist of the Hawaiian Volcano Observatory, U. S. Geological Survey. Earlier, it had been discussed repeatedly with the late Thomas A. Jaggar, Ruy H. Finch (my predecessor as director of the Observatory), and Chester K. Wentworth. Although minor differences of opinion exist, I believe we agree on essential points.

Curtis Kamai, engineer for the Territorial Highway Department, through the courtesy of that department, worked closely with us during the 1955 eruption and paid special attention to the behavior of flows in relation to barriers. Discussions with him during and since the eruption are gratefully acknowledged.

Doak C. Cox, geologist for the Hawaiian Sugar Planters' Association Experiment Station, has contributed valuable discussion of the manuscript.

NEED FOR PROTECTION

Hilo Bay lies at the junction of the slope of Mauna Loa volcano with that of Mauna Kea to the north (Fig. 1). Most of the city of Hilo, south of the Wailuku River, is built on geologically recent lava flows from Mauna Loa. The very existence of Hilo Bay is the result of these flows, which constitute all of the broad promontory that extends eastward to Leleiwi Point. These flows cannot now be dated in years, but probably most of them are less than 2,000 years old.

Since about 1820, when our real knowledge of Hawaiian volcanoes begins, Mauna Loa has been among the most active volcanoes in the world. During that period it has erupted on an average once every 3.6 years, and the total lava poured out has been more than 4 billion cubic yards. Nothing in the geological record indicates that this degree of activity is abnormal in the history of the volcano, nor is there reason to expect that the degree of activity in coming centuries will differ appreciably from that of the last.

The vents of flank eruptions of Mauna Loa are concentrated along two zones of fracturing, known as rift zones, that extend respectively east-northeastward and southwestward from the summit of the mountain. The northeast rift zone averages about a mile in width, and trends almost directly toward Hilo. It is marked at the surface by innumerable fissures in the ground, and lines of cinder and spatter cones built at the sites of eruptions. The three small cinder cones known as the Halai Hills, within the city of Hilo itself, appear to lie on the prolongation of the northeast rift zone; but fortunately the portion of the rift zone below an altitude of 6,000 feet has been inactive for many hundreds of years. Eruption along the northeast rift zone has built a broad, rounded ridge trending toward Hilo. The north slope of this ridge intersects the south slope of Mauna Kea, producing a broad valley through which the Wailuku River and its tributaries flow eastward into Hilo Bay (Fig. 1). Because of this topographic configuration, all lava flows erupted from the northern part of the rift zone below approximately 11,500 feet altitude are directed toward Hilo within a belt about 6 miles wide. Whether or not they reach Hilo depends largely on the volume of lava released during the eruption, and whether it is concentrated into a single flow or spread as several flows over the upper slope of the mountain.

It is the restriction of flows approaching Hilo to this relatively narrow (6 miles wide) belt just south of the Wailuku River that makes feasible the protection of the city by diversion barriers.

Flows issuing at points on the northeast rift zone above 12,000 feet altitude probably will turn westward in the Humuula Saddle (as did the flow of 1843), and consequently do not constitute a threat to Hilo.

Since 1850 there have been 6 major eruptions in the northeast rift zone, producing 8 major lava flows with an aggregate volume of

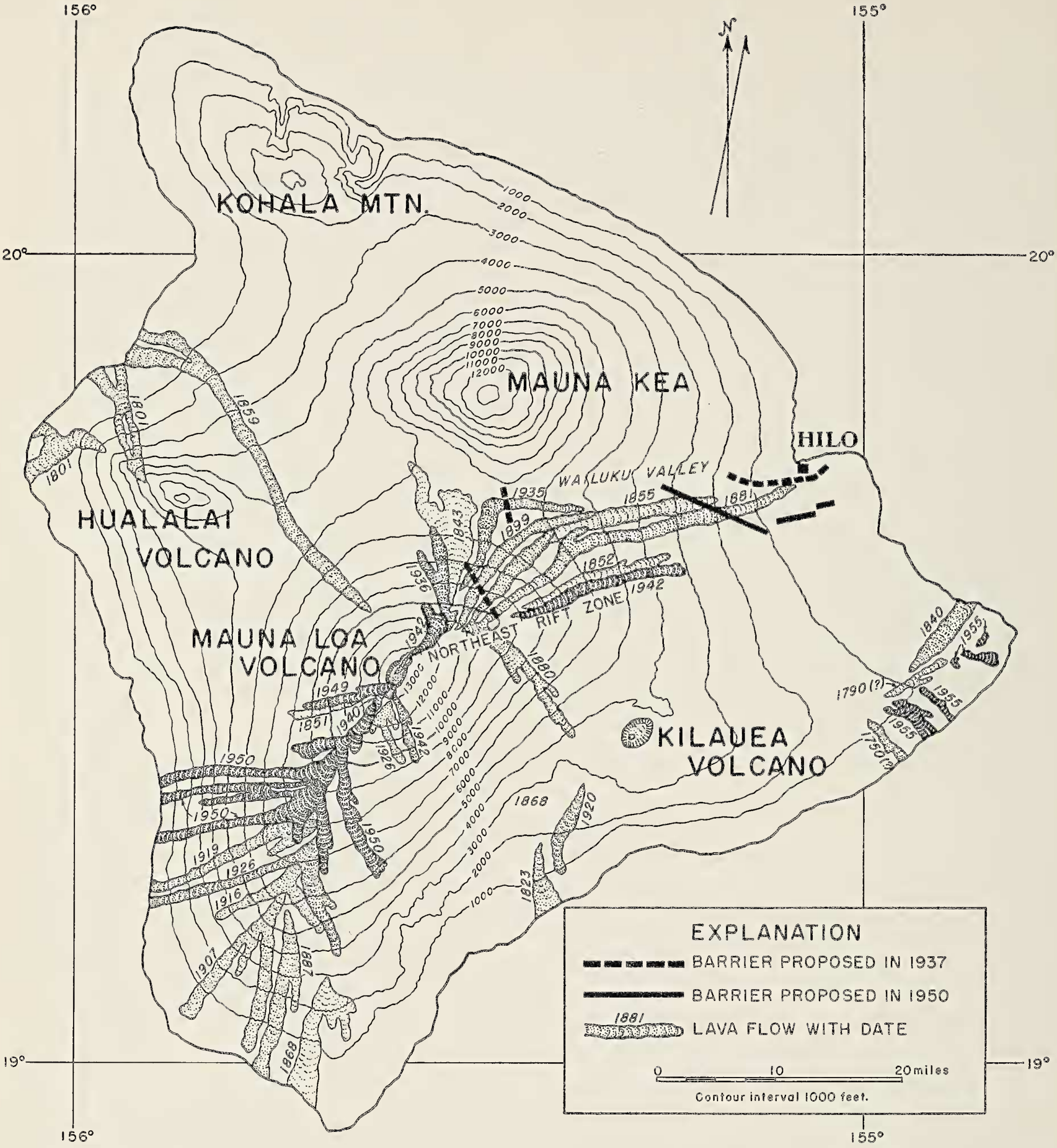

FIG. 1. Map of the island of Hawaii, showing the location of the city of Hilo, and of barriers proposed to protect it from lava flows originating on the northeast rift zone of Mauna Loa.

more than 1,000,000,000 cubic yards. Of these, 7 flows have advanced toward Hilo, and in 1881 lava actually invaded part of the present city. The volume of the 1881 flow toward Hilo was approximately 250,000,000 cubic yards. In 1942, a flow with a volume of approximately 100,000,000 cubic yards started from a vent at 9,200 feet altitude and advanced northeastward 16 miles, coming to a halt 12 miles from the shore of Hilo Bay. As compared with these flows from the northeast rift zone, the 1859 flow on the northwest slope of the mountain and the 1950 flows from the southwest rift zone each had a volume of approximately 600,000,000 cubic yards. This latter volume is more than twice that of the 1881 flow, and 6 times that of the flow of 1942. The distance from the source of the 1859 flow to the point where it entered the ocean is 32 miles. The vents of the 1942 and 1881 flows are 28 and 30 miles, respectively, from the shore at Hilo. If either the 1881 or the 1942 flows had had a volume equal to that of the 1859 or 1950 flows, the lava almost certainly would have entered Hilo Bay, and doubtless would have overrun much of the city.

In the vicinity of Hilo, lava flows of geologically recent age rest on a bed of yellow ash (Stearns and Macdonald, 1946: 63–78), and early flows of this group buried charcoal that has been shown by radio-carbon dating to have been formed about 2,000 years ago (Macdonald and Eaton, in preparation). It is estimated that during the interval since then about 20 or 25 lava flows have entered the Hilo area. Thus, based on these crude statistics as well as on the historic record, an average of about one flow per century can be expected to enter the city of Hilo. Probably about one of every three such flows will enter the bay. The last flow to enter the present city was that of 1881, and no flow has entered the bay since sometime previous to 1800. Obviously, these figures are inadequate for the determination of the mathematical probability of the entrance of lava into the city or harbor within any given length of time; but within their limits they suggest that a flow may be expected to enter the city within the next 25 years, and to enter the harbor within the next century. No one can predict when this may happen—whether within the next 5 years or a century or two hence—but the threat is apparent and the implications to the economy of the island demand consideration of protective or palliative measures.

The volume of water in Hilo harbor, and especially that in the deep ship channel, is comparatively small. The total volume east of a line connecting the end of the breakwater with the mouth of the Wailuku River is approximately 45,000,000 cubic yards, and in the same area the central channel below a depth of 5 fathoms has a volume of only about 3,000,000 cubic yards. Part of any flow entering the harbor would project above sea level, of course, and part would occupy the shallow margin of the bay, but the topography of the bay floor would guide the advancing flow directly into the most important part of the harbor—the ship channel. Once in this submerged valley the lava would tend to spread along it. Both the natural valley wall north of the channel, and the breakwater, would serve as barriers to confine the flow to the harbor. Thus 100,000,000 cubic yards of lava entering the harbor almost certainly would make it unusable, and half that volume probably would have the same result. Indeed, a very much smaller volume entering the ship channel, as it very probably would do, would cause serious damage.

The loss of Hilo harbor would be disastrous to the present economy of much of the island of Hawaii, for there is no other harbor in that part of the island capable of handling the cargo that moves through the port of Hilo. Furthermore, the loss might well be permanent. The congealed lava in the bay could not to any large extent be removed by simple dredging, and a difficult and very costly blasting operation would be necessary to clear the harbor.

It should be noted that in time of eruption the supply of fresh water for Hilo may present a serious problem. Most of the city's water now comes from the Wailuku River. A lava flow entering the Wailuku drainage basin might greatly reduce the volume of available water and render the remainder unusable without special treatment. During the 1855 eruption the river water became much discolored by organic matter from burned vegetation, but at that time it caused no trouble because the city's water was obtained from springs. The possibility of lava flows seriously damaging Hilo's water supply was pointed out several years ago (Stearns and Macdonald, 1946: 258) and the construction of wells to provide an alternative or supplementary water supply was suggested. Such wells should be kept within the line of the proposed lava diversion barrier, protected as far as possible from lava flows.

INADEQUACY OF AERIAL BOMBING

The use of explosives to alter the course of lava flows was first suggested by the late Lorrin A. Thurston in the early 1920's, and was elaborated and made specific by Jaggar (1931, 1936). The idea of emplacing the explosive by means of aerial bombs was suggested by the late Guido Giacometti at the time of the 1935 eruption.

There are three general ways in which bombing can divert lava flows: (1) by breaching a lava tube in a pahoehoe flow, (2) by breaching an open channel in an aa flow, or (3) by breaking down the walls of the cone at the vent (Finch and Macdonald, 1949; 1951: 128–132). (For a discussion of the characteristics of aa and pahoehoe flows, see Macdonald, 1953.)

(1) At first the main feeding streams of all flows are in open channels, but after the first few hours or days of activity the main stream of a pahoehoe flow crusts over and develops a roof. Thereafter it flows through a tube, from a few feet to as much as 50 feet in diameter, resembling a great pipe or subway. Bombs dropped on this tube may break it open, clogging the tube partly with debris from the shattered roof and partly with viscous aa lava resulting from the violent agitation of the fluid lava in the tube. The clogging may cause an overflow from the tube at that point and a consequent diversion of the main feeding stream of the flow. If the diversion is several miles upstream from the former advancing flow front, several days may pass before the front of the new flow reaches as great a distance from the vent as had the earlier flow front.

(2) The main feeding river of an aa flow remains largely open, but repeated overflows gradually build up natural levees on each side of the stream, and after the first few days the stream commonly is flowing at a level several feet higher than the adjacent land surface. Breaking down the levee by bombing permits the liquid to escape from the old channel and start a new flow. The removal of part or all of the supply of liquid lava from the old channel causes the advance of the old front to slow greatly or stop altogether, and it may be several days before the new front reaches a point as far from the vent as that reached by the old one. At that time bombing can be repeated if necessary.

(3) Commonly the pool of liquid lava in the cone, which feeds the flow, is at a level several feet above the ground surface adjacent to the cone. As with the aa levees, breaking down of the walls of the cone allows the lava to spill out laterally, starting a new flow and depleting the supply of lava feeding the previous flow.

The last method, suggested independently by Finch (1942) and the writer (Macdonald, 1943), has not yet been tried, although the natural breakdown of the cone walls during the 1942 eruption produced essentially the same effect that would be brought about by bombing. The first method was employed under the direction of Jaggar in 1935, and the second under the direction of Finch in 1942. In neither case did the bombing wholly divert the flow, but in both it was demonstrated that the methods can be successful under favorable circumstances. However, bombing methods can be used only where topography is favorable and at times when the lava flow has formed well-developed tubes or channels between elevated levees, or when a large cone of appropriate shape has been built at the vent. Furthermore, the bombs must be very accurately placed to produce the desired effects, and this in turn requires good visibility of the targets from the air. During times of eruption visibility is often very poor over the flows in any area because of the clouds of volcanic fume and smoke from burning forests. In the area southwest of Hilo visibility is apt to be especially poor because of the combination of these with the normal trade-wind clouds generally present even in times of noneruption. For days or even weeks at a time targets in that area may not be visible from the air. This is emphasized by experience during the 1942 eruption, when the most favorable targets chosen during a reconnaissance flight could not be seen on succeeding bombing flights, and the bombs had to be dropped on less favorable targets.

Possibly the bombs could be placed accurately, even in dense clouds and smoke, by the use of infrared or radar bomb sights. Also it has been suggested that heavy artillery fire, directed by ground observers close to the targets, might be used instead of bombing in order to overcome the difficulties of poor visibility from the air. The method should be tried. It appears doubtful, however, whether the explosive charges delivered in that manner could be sufficiently large to produce the desired results.

Still another limitation to the use of bombing arises from the considerable length of time required to load planes with bombs and fly them to the scene of eruption, and to select targets. Rapidly moving flows may already have done their damage by the time the bombers arrive. Thus, for instance, the lava flow that destroyed part of Pahoehoe village on the night of June 1, 1950, could not have been diverted by bombing because of the very short time (about 3 hours) in which it reached the village, and because its channel walls were not sufficiently well established to permit them to be broken down by bombs. The same would be true of a similar rapid flow toward Hilo. Fortunately, a flow of equal rapidity is unlikely in the area near Hilo, because of the much gentler slopes on the Hilo side of the mountain and the much greater distance of Hilo from any likely vents. Nevertheless, flows too rapid to be bombed successfully before they reach Hilo are possible. The lava flow of 1859 traveled the entire distance of 32 miles from the vents to the ocean in less than 8 days, over slopes averaging about the same as those southwest of Hilo.

Thus bombing cannot be relied upon to protect Hilo from lava flows. It is a useful auxiliary method, and should be employed when possible even if lava barriers have been built, to help preserve the barriers in a condition of maximum usefulness for future eruptions.

EFFECTS OF LAVA FLOWS ON WALLS

The idea of constructing walls to control the course of lava flows is not new. In 1881, a loose stone wall was hastily constructed across what was then the course of Alenaio Stream, in an attempt to prevent the lava from reaching the Waiakea mill (on the southern outskirts of Hilo). The pahoehoe lava reached the wall, formed a pool behind it, and eventually spilled over the wall without displacing it. This is an interesting illustration of the ability of even a loose stone wall to withstand the thrust of a lava flow. By chance, the flow stopped when the lava had progressed only a few feet beyond the wall. If the flow had not stopped, the attempt to confine the lava was doomed to certain failure because the wall was built as a dam directly across the course of the flow, and even though the wall confined the liquid lava for a short time the reservoir was too small to hold any great volume of lava.

Also in 1881, a much greater project in the Hilo area was planned, but never executed. W. R. Lawrence, an engineer for the Hawaiian government, recommended the construction of an embankment along the northern side of Alenaio Gulch to confine the lava to the gulch and prevent it from spreading northward into the main part of Hilo. Arrangements were being made to put 1,000 men to work on the project, when the flow ended and the construction became unnecessary (Baldwin, 1953: 3). If the project had been carried out, it probably would have been successful.

For many years farmers on the slopes of Vesuvius have built small walls in an effort to keep mud flows from entering their vineyards, but the method does not appear to have been employed against lava flows (F. M. Bullard, personal communication, 1956). Except for the barriers built in 1955, described on a later page, I know of only one other deliberate attempt to control a lava flow by means of a wall. In 1951, lava flows from Mihara volcano, Japan, accumulated in the Oshima caldera and approached the level of a low gap in the caldera wall directly above the village of Nomashi. In an effort to prevent the lava from spilling through the gap and threatening the village, the villagers constructed across the gap a masonry wall (Fig. 2) 15 meters long, 2 to 4 meters high, and 3 meters thick (Mason and Foster, 1953: 257). The wall was intended to impound the lava like a dam, until the lava reached a level at which it would spill through another nearby gap where it would not threaten the village. The eruption stopped before the lava reached the wall, but there is every likelihood that the wall would have accomplished its purpose.

Several examples of lava flows coming in accidental contact with stone walls have been observed. In 1906, an aa lava flow invaded the town of Boscotrecase, on the south slope of Vesuvius, and entered the churchyard which was enclosed by a masonry wall about 10 feet high. The lava filled the churchyard nearly to the level of the top of the wall, but did not damage the wall (Jaggar, 1945: pl. 1). Nearby, lava moving along the village streets did not seriously disturb the walls of the adjacent buildings (Fig. 3). Most of the damage to the masonry, visible in Figure 3, was caused by fire in the buildings. (At other places buildings were seriously damaged, especially where the walls lay at right angles to the direction of advance of the flow.)

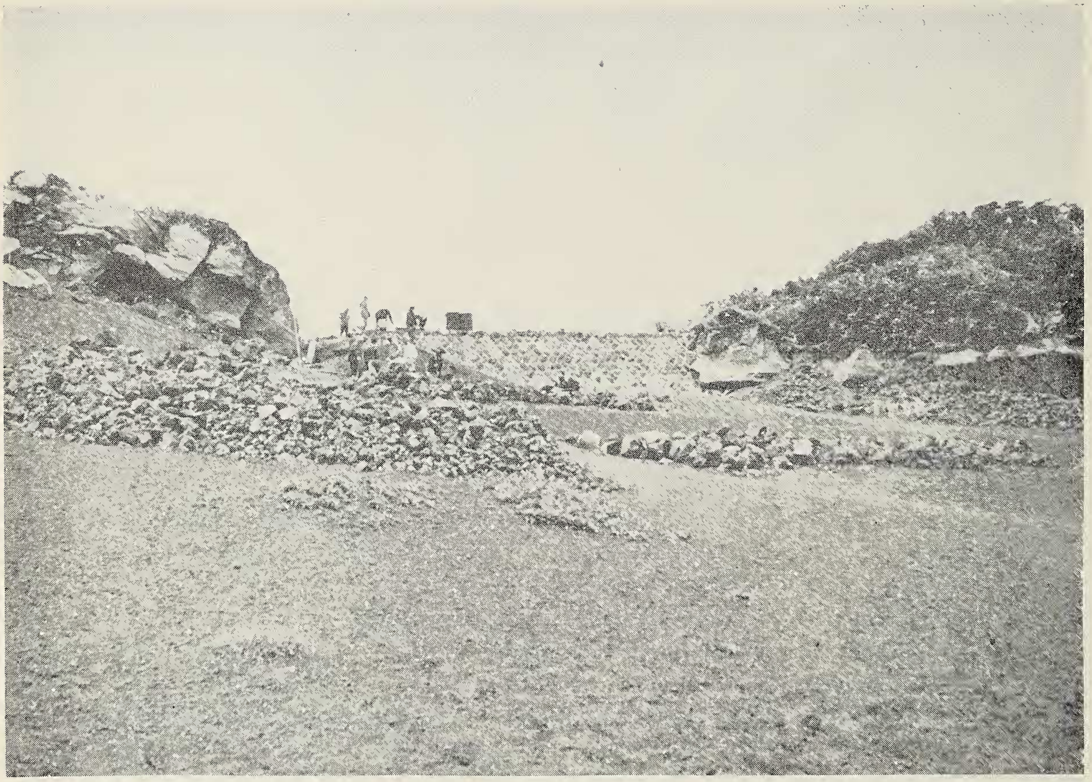

FIG. 2. Masonry wall built across a gap in the wall of Oshima caldera, Japan, in 1951, to prevent lava from spilling through the gap and endangering the village of Nomashi. Photo by Helen L. Foster, U. S. Geological Survey.

FIG. 3. Lava flow filling a street in the village of Boscotrecase on the slope of Vesuvius during the eruption of 1906. Note that the masonry walls are little disturbed. Photo by T. A. Jaggar.

In 1920, a flow of pahoehoe transitional to aa, from the southwest rift of Kilauea, encountered a loose stone wall 2.5 to 3 feet high and 18 inches thick lying at an angle of about 60° to the course of the flow, piled up behind it, and eventually spilled over it without damaging the wall (Jaggar, 1945: pl. 2). Before spilling over the wall the flow was diverted for 40 feet along its length. In 1935, a pahoehoe flow from Mauna Loa encountered a similar wall in the Humuula Saddle and formed a pond behind it until the level of the lava became high enough to spill over it, again with almost no effect on the wall itself. In 1954, a pahoehoe flow on the floor of Kilauea caldera surrounded an old corral on three sides, but did not push over its loose stone walls, which actually were in such poor condition that they were starting to tumble down by themselves. In 1950, a rapid aa flow on the west side of Mauna Loa encountered a loose stone wall about 3 feet high along the upper side of the highway. The lava soon piled up enough to spill over the wall, but it does not appear to have damaged the wall, and for a distance of about 250 feet at the south edge of the flow it spread only 15 to 20 feet beyond the wall. Farther north the same flow continued unchecked down the mountainside (Finch and Macdonald, 1950: 4).

An excellent example of the effect of unsubstantial walls on fluid lava is contained in the following description by Jensen (1907: 653) of the lava flow of 1905 at Matavanu, Samoa:

> In portions of the coastal area, as at Toapaipai, where the thickness of the flow is between 10 and 40 feet, the lava has in several instances flowed round buildings of stone, piling itself higher and higher, without crushing in the walls. Such houses are now represented by holes, except where the flow has been sufficiently high to enter by the roof, or sufficiently liquid to . . . flow in through the windows. At one place, near Saleaula, where the lava is between 6 and 10 feet thick, a native house was removed before the stream advanced, but the spot where it stood is now a depression surrounded by almost vertical lava walls and has grass growing on the bottom. This spot was preserved by a ring of stones about 18 inches high, such as the natives make round their houses.

The latter constitutes a remarkable extreme example of the ability of walls to hold back lava flows of depth much greater than the height of the wall. This characteristic will be discussed in more detail below.

Mason and Foster (1953) have described the destruction of a tea house on the rim of Mihara Crater in 1951. As the lava surrounded the building, wooden parts were destroyed by fire and lava which entered through window openings, but the masonry walls withstood the pressure of the flow.

During the 1669 eruption of Mount Etna in Sicily, lava flowed against the ancient city walls of Catania. For several days the walls withstood the lava and diverted it around the city toward the sea (Sartorius, 1880: 252–253). Eventually the lava broke through a weak part of the wall and flowed into the city. It should be noted, however, that the breach occurred in a part of the wall that lay essentially at right angles to the course of advance of the flow, and hence was acting as a dam rather than as a diversion barrier.

The foregoing illustrations are ample to demonstrate that thin masonry walls, and even ordinary loose stone walls such as are built as fences along land boundaries, commonly are able to withstand the pressure of lava flows without being pushed over. As Mason and Foster (1953) have pointed out, such pressure usually is no more than the hydrostatic pressure that the lava is capable of exerting against the wall (and it will be shown that this is only a portion of the theoretical hydrostatic pressure). In some instances the forward momentum of a flow may result in sufficient pressure to push over ordinary stone walls or even masonry walls. Examples of this are known at Etna. However, even the relatively high velocity of the Kaohe flow during the 1950 eruption of Mauna Loa was not sufficient to disturb materially the loose stone wall along the highway. Fortunately, also, on the gentle slopes in the vicinity of Hilo lava flows are likely to be slow moving, thus reducing essentially to zero the risk of the momentum-pressure of a flow pushing over even a very frail wall.

EXPERIENCE WITH BARRIERS DURING 1955 ERUPTION

The most recent attempts to control lava flows in Hawaii by means of walls were made during the 1955 eruption of Kilauea. Accounts of the eruption have been, or will be, published elsewhere (Macdonald and Eaton, 1955, and in preparation).

The first possible need for a diversion barrier arose on the evening of March 3, when a big aa flow from the vents near Puu Kii reached a low divide at the head of a shallow valley that led toward the village of Kapoho. Had the flow spilled over the divide and entered the valley, it probably would have followed the valley to Kapoho. A former railroad embankment 8 to 10 feet high, currently used as a truck roadbed, lay across the top of the divide. The lava reached that embankment and piled up as much as 15 feet above it, but was deflected southward by it, away from Kapoho. Although the top of the flow stood high above the level of the top of the embankment, the movement of the flow was governed by the lower liquid portion, on which the top was merely carried along. The behavior of the flow in this instance clearly demonstrated that under favorable circumstances

FIG. 4. Wooden plank set in the path of a pahoehoe flow on the flank of Kilauea volcano on March 13, 1955, diverting the flow.

FIG. 5. Bulldozers constructing an earthen barrier in an attempt to keep lava from reaching the Iwasaki camp during the eruption of Kilauea on March 21, 1955.

the height of a barrier need not be as great as the depth of the lava in order to turn the course of the flow.

The next experience with a barrier came on March 13, when fluid pahoehoe flows were erupted in cleared land adjacent to the Pahoa-Kalapana road. Seizing a favorable opportunity, we placed in the path of one of the advancing flow tongues a wooden plank about 8 feet long, 18 inches wide, and 2 inches thick. The plank was set on edge in nearly vertical position, diagonally to the path of the flow, and held in place by a few loose rocks placed behind it. The intense heat of the approaching flow front prevented us from doing a good job of blocking the plank in place. The lava came in contact with the plank and tilted it back to a somewhat flatter angle, but the lava was turned to one side by the plank, and in spite of the insecure blocking did not push the plank aside (Fig. 4). The plank ignited and burned slowly, but continued to divert the flow for half an hour, until a new tongue of lava approached it by a different path and buried it.

On the morning of March 21 a tongue of a large aa flow entered the head of a small valley that led directly to a small plantation camp owned by Koji Iwasaki. It was obvious that if the lava continued down the valley the camp was doomed. In an effort to divert the flow across the low ridge south of the valley, a wall about 1,000 feet long and averaging about 10 feet high was hurriedly thrown up by bulldozers (Fig. 5) working under the direction of Arthur Lyman of Olaa Sugar Company, with the advice of J. P. Eaton of the Hawaiian Volcano Observatory staff. During the afternoon the flow front reached the barrier, and was successfully turned by it. However, after the flow front had moved only about 50 feet along the barrier the supply of lava was cut off, and that tongue of the flow stagnated.

Later in the eruption another flow tongue came against a different part of the barrier. But again, after the lava had moved along the barrier only a few feet, the flow stopped. Still later flows swept down the mountainside by other routes remote from the barrier and destroyed the Iwasaki camp.

Thus, the Iwasaki barrier was not actually subjected to a critical test. However, it does supply some valuable data on barrier construction. The wall was built by 6 bulldozers (three D-8's, two D-7's, and one TD-14) in less than 4 hours, working in an area of old pahoehoe flows where loose material available for incorporation in the wall was not abundant. At times the bulldozers worked within a few feet of the advancing flow front without trouble, and after the first few minutes without undue worry to the operators. Because of the small amount of space available, the wall was placed at too flat an angle to the course of advance of the flow for best results. Nevertheless, the flow front was successfully turned. The flow piled up to nearly double the height of the wall, but only a few fragments rolled over the wall.

About noon on March 22, Robert Yamada started construction of another series of barriers to try to divert another portion of the flow from his coffee plantation near the coast. The work was done by four TD-24 bulldozers under the supervision of Yamada's son, Donald. The first barrier was placed at much too obtuse an angle to the course of the advancing flow. Moreover, the terrain was not really favorable to the successful operation of diversion barriers. The drainage system is poorly defined, and the slope of the land surface is so low that barriers need to be placed at a very acute angle to the course of the flow in order to provide sufficient grade in the new channel behind the barrier. A plan of the Yamada barriers is given in Figure 6.

At 3:30 p.m. on the same day a tongue of the lava flow was advancing down a road toward the barrier at a rate of about 60 feet an hour, with its front only 260 feet from the growing barrier. It became evident to Curtis Kamai and me that this tongue would reach the barrier before the main body of the flow reached it somewhat farther upslope, and

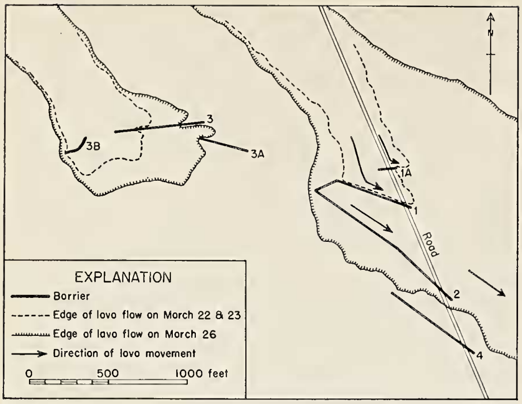

FIG. 6. Plan of the barriers built by Robert Yamada in an attempt to keep lava from destroying his coffee plantation, on March 22–24, 1955.

might consolidate against the barrier to form a dam which would impound the main body of the flow against the barrier and cause it to spill over. To prevent that, a short barrier (Fig. 6, 1A) about 150 feet long and 8 feet high was hurriedly built across the path of the rapidly advancing tongue. This short barrier was completely successful. Part of the flow was diverted eastward by it, but, more important, the advance of the entire tongue was delayed, as had been hoped, until the main body of the flow had made contact with the main barrier farther west and the entire flow front had turned eastward along the main barrier.

On completion of the first two barriers (Fig. 6, 1 and 1A) construction was started on another (Fig. 6, 2) farther down slope and lying at a more acute angle to the course of advance of the flow. Barrier 2 was connected to barrier 1 by a short wall at its western end. This connection was a mistake because it prevented the full operation of barrier 2 and actually forced some lava to flow around its western end, thus partly defeating its purpose. Lava spilled over barrier 1, which as previously stated was built at too obtuse an angle to the path of the flow, and filled the space between barriers 1 and 2. On March 24 a strong flow of lava was observed by Eaton along the north side of barrier 2 and parallel to it. Some lava spilled over barrier 2, particularly near its western end where it was only about 6 feet high, and joined that flowing around its west end, but the main body of lava was diverted eastward. No lava reached barrier 4 (Fig. 6).

Barriers 3, 3A, and 3B, to the west of barrier 2 (Fig. 6), were poorly conceived and served no useful purpose. In particular, barrier 3B, which appears to have been an attempt to impound a flow tongue by heaping up a wall around it, was wholly ineffective.

In spite of poor placement and hurried, inadequate construction, the principal Yamada barriers were essentially successful. Very little lava passed barrier 2 in the direction of the coffee plantation, and even at the time of poorest operation of the barrier Eaton estimated that the velocity of flow of lava along the north side of the barrier was 5 times as great as that across it. Considering the much smaller depth of material crossing the barrier as compared with that in the channel behind it, this means that probably at least nine-tenths of the volume of the flow was diverted eastward parallel to the barrier.

Unhappily, these courageous attempts at barrier construction on the part of the Yamadas did not prevent the destruction of the coffee plantation. On March 27 another flow passed a quarter of a mile southwest of the barriers, and on March 28 it swept across the plantation and into the ocean.

The Yamada barriers provided some important lessons in barrier construction. In the first place, they demonstrated the amazing rapidity (and correlatively, the surprising cheapness) with which such barriers can be built by modern bulldozers in areas where construction material is abundant. The area was one of fairly recent aa flows, and large amounts of loose aa clinker could easily be pushed up (together with tree trunks and all other debris) into a wall. Careful observation by Eaton, Kamai, and myself revealed no signs of any yielding of the walls under the thrust of the lava flows. The short delaying barrier (Fig. 6, 1A) was entirely successful, and demonstrated one method of controlling the relative speed of advance of different parts of a flow front. Barrier 2 showed that even when the flow top has piled high above the barrier, and some spill-over is occurring, the barrier may still control the direction of movement of the bulk of the flow. The Yamada barriers demonstrated also the importance of a cleared corridor along the upper side of the barrier, to facilitate the advance of the flow along the barrier; the importance of placing the barrier at an acute angle to the course of the flow, and maintaining a continuous downgrade in the new channel created by the barrier; the importance of extending the barriers laterally sufficiently far to be certain of catching all flows that may advance toward the area being protected; and finally, the importance of planning and building in advance, thus avoiding the poor execution attendant on hurried construction with the lava crowding the bulldozers.

As it crossed the Yamada coffee fields, the lava provided yet one more lesson on lava barriers. In clearing the fields, bulldozers had pushed up great heaps of trash, 10 feet or more in height. These heaps consisted largely of trunks and branches of pandanus trees, with smaller amounts of other vegetable debris and some rocks. The lava flowed between, and eventually over, the heaps of loose and mostly light rubbish without to any important degree displacing them, thus again demonstrating the small amount of thrust exerted by lava on obstacles. A similar example occurred earlier in the eruption at the time of the outbreak at the edge of Kapoho village, when a heap of rubbish that had been pushed aside in clearing land diverted the flow away from a house. The Kapoho flow was a thin and very fluid pahoehoe flow, and might be expected to be easily diverted. The flow through the Yamada coffee fields was a very active aa flow with a moving front 10 to 15 feet high, and might be expected to exert as much thrust against an obstacle as almost any Hawaiian flow; yet even it exerted so little thrust that the piles of loose debris in its path were essentially undisturbed by it.

The fact that lava flows follow the path of least resistance was demonstrated repeatedly during the 1955 eruption. The flow fronts advanced much more rapidly along roads than through adjacent cane fields or forests. Even the small amount of obstruction caused by small and relatively scattered vegetation obviously slowed the advance of the lava. At the Yamada barriers, the lava covered the ground cleared by the bulldozers during construction of the walls much more rapidly than it did the uncleared forest areas. This fact is important because it indicates the great desirability of clearing and keeping reasonably clear a path 500 or more feet wide along the upper side of a diversion barrier to aid in turning the flow and establishing a channel along the barrier.

PRINCIPLES GOVERNING LAVA MOVEMENT

Certain basic facts in the behavior of lava flows are of fundamental importance to the operation of lava barriers. These facts may be briefly enumerated.

Although every lava flow has some solid portions, the movement of the flow is governed by the liquid portions. The solid portions are passively dragged along by the liquid, tending to modify somewhat the behavior of the liquid, principally by making it more viscous; but, especially in Hawaiian flows, these modifications are small. The fact of basic importance is that the flowing lava is essentially a liquid and for the most part behaves like one. Thus lava always tends to flow directly down the steepest available slope, and to follow the path of least resistance.

In aa flows the most fluid portion is restricted to a narrow feeding river, seldom more than 30 feet wide, usually situated near the center of the flow. The margins of active flows commonly are still mobile, but very much less so than the material in the feeding river. Similarly, pahoehoe flows are fed by narrow streams flowing through natural pipes, or lava tubes. The modes of advance of both types of flows have been described elsewhere (Macdonald, 1953).

The viscosity of lava flows is high. Even in the most fluid portion, close to the vents where the temperature and gas content are highest and the load of solid crystals and rock fragments is least, the viscosity is 300,000 to 400,000 times as great as that of water (Macdonald, 1954: 173). Farther from the vent the viscosity of the most fluid portion rises to a million and more times that of water, and the effective viscosity of the flow as a whole is still higher. The liquid has a specific gravity probably 2 to 2.5 times that of water. Thus the liquid is both heavy and viscous. On steep slopes the heaviness of the liquid results in high speeds of flow, locally up to about 30 miles per hour, in spite of the high viscosity. However, such high speeds are attained only in the narrow feeding channels or tubes. The high viscosity of the lava normally results in slow movement of the main body of the flow. On the steep slopes in central Kona the first flow of the 1950 eruption advanced as a whole at an average rate of 5.6 miles per hour. However, on slopes such as prevail on the side of the mountain toward Hilo the fastest observed advance of a flow front is only about 1,000 feet per hour, and most flow fronts advance much more slowly than that. The flows of 1855 and 1881, on the slope of Mauna Loa southwest of Hilo, advanced only a few tens or hundreds of feet a day on the middle and lower slopes of the mountain.

In almost all instances, essentially the only force causing movement of the flow front is the component of gravity along the sloping surface over which the lava is moving. Because ground slopes in Hawaii generally are low, the component of gravitational force generally is small. This, combined with high viscosity of the liquid, results in the observed slow speeds of flow. In turn, because of their slow movement, lava flows possess very little kinetic energy. Where high speeds occur, the moving liquid may have enough kinetic energy to cause it to dash a few feet up slopes opposed to the direction of flow, or be thrown a few feet into the air where it encounters obstacles. Such occurrences are comparatively rare, however, and are encountered only on unusually steep slopes in the narrow feeding channels or very close to the vents. They are never encountered at flow fronts more than a very few thousand feet from the vents. Likewise, the viscosity of the lava, though high, is not sufficiently great to permit much thrust on the flow front from lava behind it. Thus Hawaiian lava flows will not advance up hill to any extent, or exert any appreciable impact pressure against an obstacle owing to energy of motion in the flow. A flow front encountering a barrier will not tend to "climb" the barrier to any important extent, nor will it strike against it with any violence. The lava will accumulate behind the barrier until an equilibrium level is attained, just as would water or any other liquid, and if the depth of the lava becomes great enough it will spill over the barrier. But essentially the only pressure exerted against the barrier is a portion of the hydrostatic pressure of the lava in the pool.

Wentworth (1954) has pointed out that, although essentially a liquid, lava does not behave quite like water or other familiar liquids. The difference results largely from the much greater viscosity of lava, and its tendency to freeze, thereby building up and tending to clog its channel, with consequent irregular overflows. This building up of the channel makes possible one type of diversion by aerial bombing, mentioned earlier. The most obvious effect of the high viscosity coupled with the tendency to freeze is the piling up of lava to form a broad mound instead of a thin sheet, as water would do. The margins of flows are abrupt scarps several feet or tens of feet high. The effect is confined largely to the flow edges. Most flows have broad nearly level (though irregular) tops, determined by the essential attainment of liquid equilibrium. The effect of viscosity and freezing at the edge of the flow, allowing the flow to stand as a self-contained unit with steep margins, is important in the operation of lava barriers in greatly reducing the hydrostatic pressure exerted against a barrier. Actually, the thrust against a barrier as a result of hydrostatic pressure is only a small fraction of what it would be if the lava were a completely liquid pool with the fluidity of water.

The ability of even loose stone walls to withstand the pressure of flows indicates that the full theoretical amount of hydrostatic pressure is not exerted laterally by the flow. Calculations indicate that with fully liquid lava resting against a wall of loose rock, sliding of the wall would result when the depth of the liquid against the wall slightly exceeded the thickness of the wall. Commonly, however, a lava flow piles up behind a wall to a depth several times as great as the thickness of the wall without displacing the wall. Apparently the departure of the fluid lava from complete liquidity is sufficiently great to prevent the full theoretical hydrostatic pressure within the flow from being transmitted to the forward edge. This is further confirmed by the frequently observed tendency for a flow to stop with only its lowermost edge in contact with some natural obstacle, such as a crater wall, leaving a moat a few feet wide between the obstacle and the higher part of the flow margin.

FACTORS INFLUENCING EFFECTIVENESS OF BARRIERS

The tendency of lava to build up its channel to a high level is important to the operation of lava barriers in two respects. One is the possibility that the flow may build up so high as to spill over the barrier. There is little danger of this if the angle of the barrier to the flow course is not too great—that is, if the barrier does not force the flow to turn too sharply. A little spill-over may be expected in any case, but is unimportant if most of the flow turns and follows the barrier. Experience at the old railroad embankment near Kapoho and at the Yamada barriers, in 1955, clearly indicates that the lower part of the flow largely controls the direction of movement of the whole flow. A well-placed barrier can be confidently expected to turn the initial flow of a group, even though it is considerably thicker than the barrier is high. Once the flow is turned, the main channel will develop parallel to the barrier, but probably several tens of feet distant from it because of the cooling effect of the barrier and frictional retardation of the edge of the flow against the barrier.

If the flow continues for a long period, the walls confining the main channel may build up to form natural levees rising to a level higher than the barrier. A breakdown of the levee could then release a flood of lava over the barrier, possibly establishing a new flow course over the barrier in addition to, or even instead of, that parallel to the barrier. Such breakdowns and lateral floodings are common near the vents, especially on steep slopes and where the channel makes an abrupt bend, but they are very rare on well-established flows at a distance from the vents. Provided the angle of the barrier to the natural flow course is kept small, the danger of such a breakdown of the channel levee at a barrier distant from the vents is very small.

More probable is a breakdown of the levee near the vents, far up slope from the barrier, producing a new major tongue of the flow. In early stages of eruptions this is a common event, and it sometimes occurs even in late stages. It may pose by far the greatest threat to the success of a lava barrier. If the new flow tongue encounters the barrier on the upslope side of the older tongue, which is already against the barrier, it may be impounded between the barrier and the older tongue, accumulate until it overtops the barrier, and flow on down the mountainside. The effectiveness of the barrier is then partly or wholly lost (although it may continue to divert the first tongue and thus reduce the amount of lava advancing toward the area under protection). Fortunately, it is rare that more than one flow tongue reaches a distance from the vents as great (12 or more miles) as that of the proposed main Hilo barrier from the active part of the Mauna Loa rift zone. Once a tongue reaches that great a distance from the vents it generally is well established as the principal flow tongue of the eruption. But the possibility of a second tongue reaching the barrier up slope from the first must be kept in mind, and, if possible, means must be provided to cope with it.

BARRIERS PROPOSED FOR HILO AREA

Barriers Proposed in 1937. The positions of the barriers suggested by Jaggar (1937, 1945) are shown in Figures 1 and 7. The principal barrier was to start at the Wailuku River a short distance above the Pukamaui Falls (where the principal intake of the Hilo water system is located), extend 4 miles east-southeastward, then turn and extend 5 miles east-northeastward, ending about a mile south of the shore at Keaukaha. This proposed barrier was intended to divert southward any lava flows approaching Hilo along the Wailuku Valley or down the slope of Mauna Loa north of the Waiakea Homesteads. Two other shorter proposed barriers were located higher on the mountainside. One extending northwestward from the vicinity of Puu Ulaula, at 10,000 feet altitude on the northeast rift zone of Mauna Loa, was intended to divert westward flows originating on the rift zone above Puu Ulaula. The other, extending south-southeastward from near Puu Huluhulu, in the Humuula Saddle, was intended in effect to shift the Humuula divide farther east so that flows pooling in the flat area just south and west of Puu Huluhulu would spill westward instead of eastward toward Hilo.

The plan adopted in the report of the District Engineer, U. S. Engineer Department, closely resembled the original recommendations by Jaggar. The barrier close to Hilo was to be 46,750 feet long, varying in height from 20 to nearly 80 feet, with a flat top 5 feet wide and slopes of 45°. It was to be built largely of material available at the site. At stream crossings a cluster of concrete pipes of 48-inch diameter laid through the barrier would allow water to pass, but molten lava entering the pipes would quickly chill in them and solidify, plugging them. At highway crossings concrete underpasses were provided, which could be blocked with concrete stop logs when a lava flow approached. For further details of the proposed construction the reader is referred to the paper by Jaggar (1945), and the unpublished report of the District Engineer. For convenience of reference, some of the drawings of construction design are reproduced in Figure 8.

Barriers Proposed in 1950. Following the 1950 eruption of Mauna Loa, concern again increased in Hilo over the possibility of damage to the city by lava flows, and Finch and I undertook a restudy of the barrier proposal. As a result of the study, we were more than ever convinced that barriers would be effective. However, because of the growth of Hilo in recent years, we suggested that the position of the proposed barrier might be shifted southwestward from that previously advocated. The positions of both lines are shown in Figure 7. The new proposed barrier would consist of several segments. The upper and principal segment would extend from the Wailuku River at approximately 3,900 feet altitude east-southeastward about 12.6 miles to a point where the lava flow would be guided down slope by a natural drainage channel. Farther seaward other shorter barriers would direct the flow into forest land southeast of Hilo where natural topography would lead it away from Hilo city, harbor, and airport. The total length of the newly proposed barriers is approximately 17 miles, as compared to 8.85 miles for that proposed in 1940. The new line extends south of Kaumana and the Waiakea Waena suburb of Hilo, which lie outside the barriers of the earlier scheme. It also provides more complete protection for the Hilo Airport area and the Keaukaha suburb, and protects the drilled wells east of the airport, which in time of eruption might provide the major source of water for the city.

The lines indicated in Figure 7 for the course of the newly proposed barriers are intended only as suggestions of an approximate route. Their precise position should be determined by detailed surveys like those made by the U. S. Engineer Department for the route of the earlier proposed barrier.

The route laid out by that department in 1940 takes complete advantage of natural topography and crosses the contour lines at the maximum possible angle. It would protect the harbor and the central part of the city as completely as the alignments suggested in 1950. Only if it is considered economically justified to protect a larger area are the positions suggested in 1950 to be preferred.

The lines on the map show the main barrier as continuous walls, as was the barrier recommended by the U. S. Engineer Department in 1940. An alternative construction, suggested by Eaton (personal communication, 1956), is a series of short segments set en echelon to each other as shown in Figure 9A. This design would provide possible means of confining portions of the flow that may spill over any one segment of the barrier, by extending a lower segment to a point beyond the spill-over. Figure 9B illustrates the way this might be done. It should be noted, however, that it might not be possible to force the spill-over into the channel behind the lower barrier segment if the space behind that segment had already been occupied by an earlier portion of the flow. If the barrier is constructed in short echelon segments, it should be started higher up the Wailuku River than indicated in Figure 7, possibly as high as 6,400 feet (about 2 miles east of Puu Huluhulu), to avoid building the segments at a greater angle to the natural direction of flow than would be a continuous barrier and thus actually increasing the likelihood of a spill-over. The idea warrants careful consideration in relation to topographic studies of greater detail and precision than are possible on existing base maps.

Wentworth (unpublished communication, 1955) has suggested that complete reliance be placed on hurried construction of a barrier after a flow has actually started to advance on Hilo. Experience during the 1955 eruption

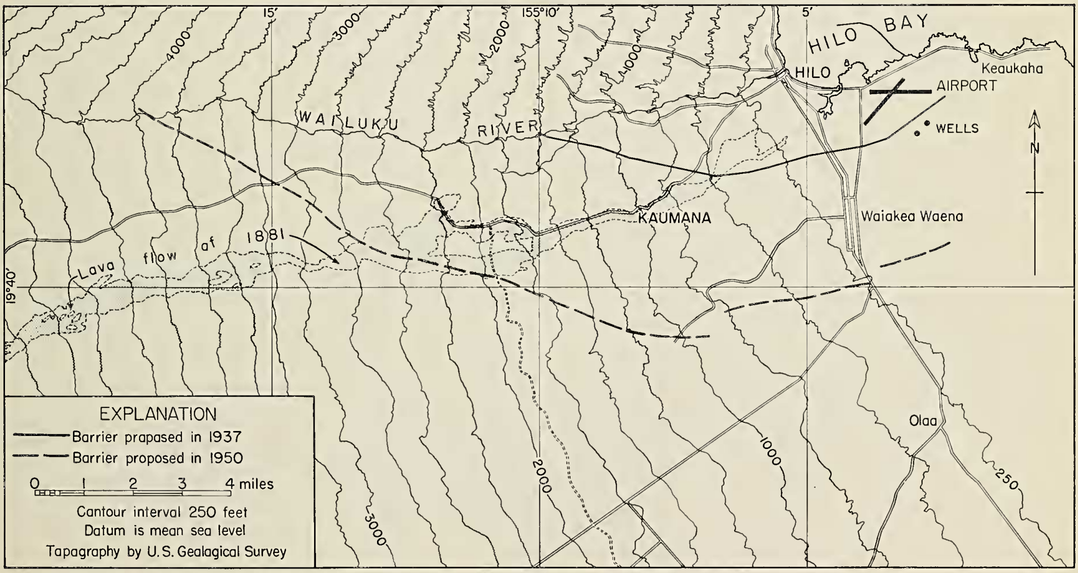

FIG. 7. Map of the area in the vicinity of Hilo, showing the route of the barrier proposed by Jaggar in 1937 and surveyed by the U. S. Engineer Department in 1940; and that of the barriers proposed by Finch and Macdonald in 1950. The latter route is only approximate.

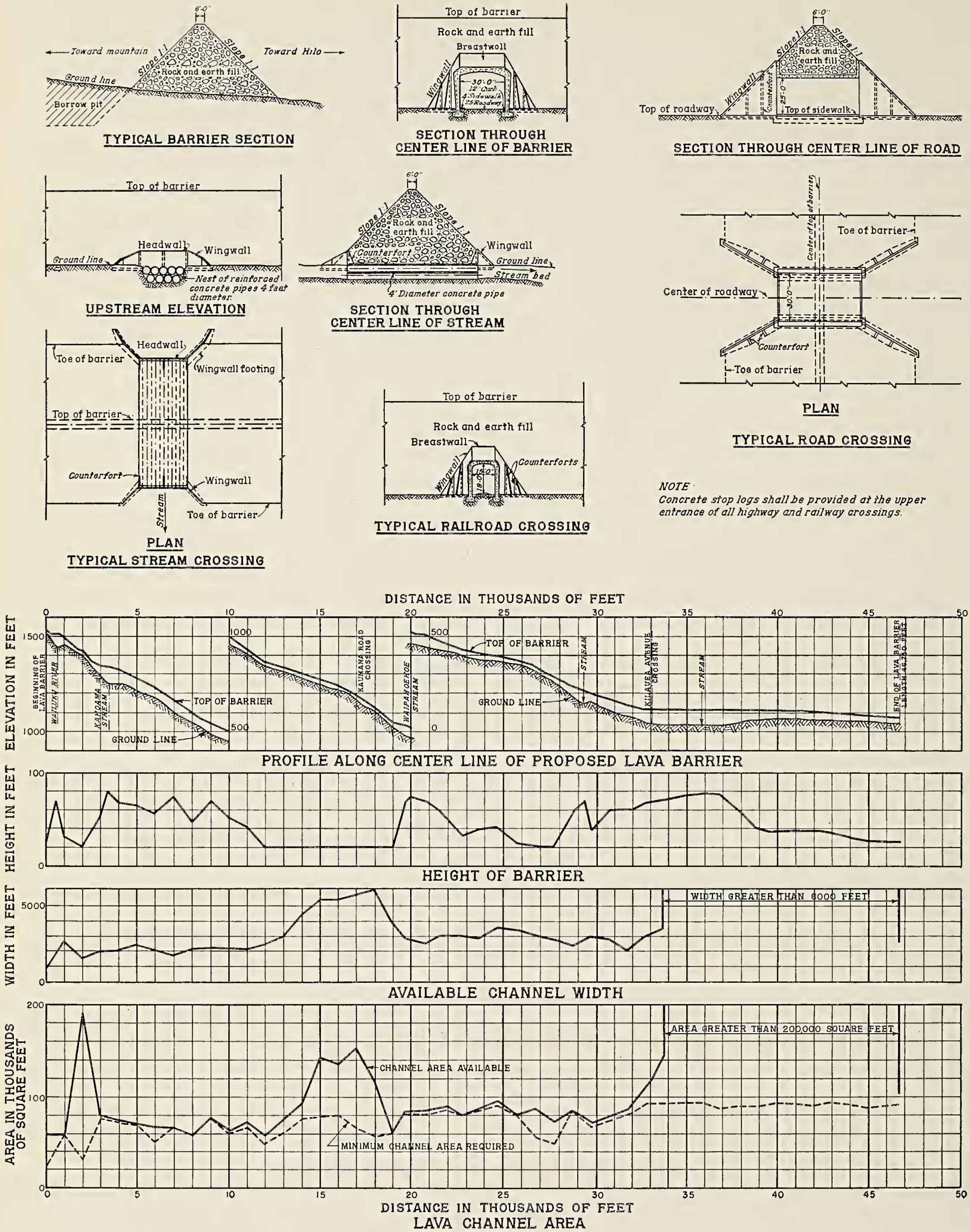

FIG. 8. Drawings showing construction design, ground profile, height, channel width, and channel volume of the barrier designed by the U. S. Engineer Department in 1940. (After Jaggar, 1945, figs. 3, 4.)

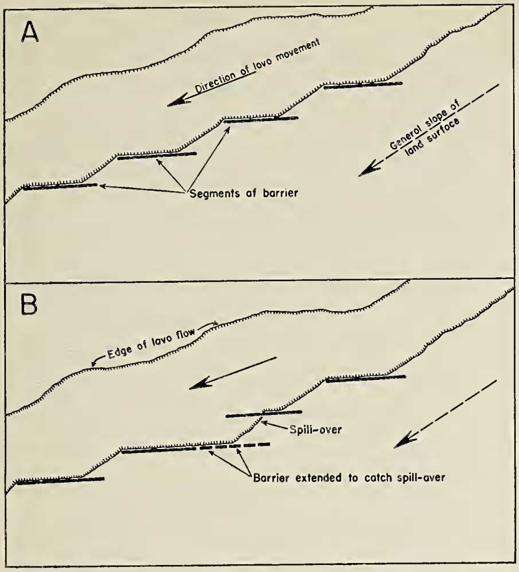

FIG. 9. A, Diversion barrier consisting of a series of short segments set en echelon. B, Manner in which one segment might be extended to catch a spill-over from the previous segment.

indicates that this is not an impossibility. It is, however, less desirable than the construction of a barrier well in advance of the need, because work done under such urgent circumstances is likely to be less well done. Time may not be sufficient to finish the job properly, and it is possible that a flow such as that of 1859 might descend the mountain so rapidly that the barrier could not be built at all. At any rate, if such emergency construction is to be relied upon, plans should be carefully prepared and a route for the barrier chosen, so that work can be started without delay or uncertainty when the need arises, and the barrier can be placed properly for maximum efficiency. Construction of the barrier should be started at its upper end, at a point determined by the course being followed by the flow, and work should progress down slope ahead of the flow.

Also, it has been suggested that a network of roads spaced about a mile apart in the area of proposed barrier construction be prepared in advance and kept clear and trafficable; but such a network appears unnecessary. Instead, a truck trail might be opened by bulldozers along the route of the barrier itself, both to serve as an access route and to mark clearly the line along which the barrier should be built when the emergency arises. Even if construction of the barrier is deferred, the route it is to follow should be marked as soon as possible so that under emergency conditions construction can proceed with minimum delay and along the correct line.

Present Views on Construction Methods. Developments in construction machinery, and experience with barrier construction and operation during the 1955 eruption, have made it apparent that barriers can be built much faster and cheaper than previously believed. Actually, the barrier need consist only of an elongated heap of rubble, obtained locally and pushed into place by bulldozers. Rock fragments should predominate, but soil and plant debris, even large tree trunks, may be incorporated. The use of excessive amounts of vegetable materials probably should be avoided in a barrier built in advance of the eruption, because such material will eventually rot away and allow the heap of rubble to slump, possibly requiring repair of the barrier.

There is no need of maintaining side slopes of 45°, or of careful dressing or smoothing of the slopes. Loose material pushed up to the required height will settle into equilibrium slopes probably between 30° and 40° from the horizontal. Such slopes are wholly saitsfactory so far as performance of the barrier is concerned. For convenience in construction, it may be desirable to build the uphill slope somewhat flatter, so that the bulldozers can convey their loads to the top of the barrier more easily.

The material for construction should be obtained entirely on the upslope side of the barrier. This has the advantage of somewhat deepening the channel created on the uphill side, for any given height of wall; and just as important, of clearing a wide swath (at least

500 feet wide) along the barrier to provide a path of easy movement for the lava.

No better design for stream crossings has been found than that suggested by the U. S. Engineer Department in the 1940 report. A bundle of concrete pipes 24 to 48 inches in diameter should be laid parallel to the stream course, and anchored in place with concrete. Above these, the barrier may consist of the same loose rubble as elsewhere.

Concrete underpasses, with concrete stoplogs, have been suggested by the department for highway crossings. An alternative, and much less costly method, would be to leave a gap in the barrier for the highway to pass through, and provide a pile of loose rubble near one side of the gap that can quickly be pushed into place by bulldozers, thus closing the gap when the flow approaches it. One advantage of the barrier proposed in 1950 (Fig. 7) is that no special crossing structure is required at the highway between Hilo and Olaa. One segment of the barrier ends just up slope from the highway, natural topography then guiding the flow across the highway to a point where it will be controlled by the next segment.

A flat top on the barrier is unnecessary, though it would do no harm. It has been suggested that the barrier might be built with a flat top broad enough to accommodate either a one- or two-lane highway. However, this would add greatly to the cost, both because of the much greater bulk of material that would have to be obtained and put in place, and because of the higher standards that would have to be set for the material and the greater care that would have to be used in construction. To successfully divert lava flows, the barrier need not even approach the standards necessary for a highway fill.

The precise height of barrier needed can be determined only by detailed surveys. The barrier must be higher than average where it crosses depressions, but can be lower where it is superimposed on natural ridges. The height of the barrier designed by the U. S. Engineer Department in 1940 averaged about 40 feet for an available channel width throughout most of its course of approximately 3,000 feet. The height was determined by the cross-sectional area of the channel behind the barrier that was considered necessary to contain a lava flow of the dimensions that might reasonably be expected to enter the area. Logically enough, the problem was approached on the basis of hydrodynamics, assuming that the lava would behave much like a stream of water under the same circumstances. As noted earlier, however, we now realize more clearly that lava does not behave wholly like water. The sides of the flow rise steeply to heights of many feet above the surrounding terrain or above a restraining barrier. It is therefore not necessary to build a barrier to a height equal to the full depth of the lava flow it is intended to divert. I believe that a barrier with an average height of 25 to 30 feet following the 1940 alignment would be adequate.

CONCLUSIONS

As a result of the foregoing considerations, I believe (1) that lava flows are certain to enter the city and harbor of Hilo eventually unless something is done to prevent their entry; (2) that they can be successfully diverted from the city and harbor by properly located and constructed barriers; (3) that no other method can be relied upon to divert the flows; (4) that construction of the barriers in advance of the eruption is preferable, but that barriers probably can be constructed in time even after the flow has started to advance toward Hilo; (5) that the barriers need consist only of loose rubble obtained locally and pushed into place by bulldozers; and (6) that the barrier alignment proposed by the U. S. Engineer Department in 1940 is adequate to protect the center of the city and the harbor, but an alignment farther southwest is necessary if it is desired to protect all of the city.

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